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Automated Internet-Based Control of Spacecraft Groundstations

Beacon-Based Health Monitoring Concept

Status Report

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1.0 Introduction

This report serves as an update about the activities of Stanford University's Space Systems Development Laboratory (SSDL) in their beacon-based health monitoring experiment. Section 1 describes the goals of the project and the organization of the team. Section 2 provides an overview of the major components of the system, describing the general approach of automated health monitoring and the beacon signal relay. It also provides background about the SAPPHIRE spacecraft and ASSET operations system, which will be used for the experiment. Specific details about implementation and status of each element of the experiment are found in Section 3. Section 4 describes the experiment and future work, and references are contained in Section 5.

1.1 General Goals

The purpose of this project is to demonstrate the feasibility of a beacon-based health monitoring concept for spacecraft in low Earth orbits. This study is an element of ongoing research at SSDL in the areas of spacecraft systems engineering, automation and operations, and is supported in part by the New Millenium Program through JPL.

Beacon-based health monitoring, within the scope of this project, is defined as a system wherein the routine task of anomaly detection is migrated from ground control to spacecraft control. The intent is to reduce operations costs by reducing both operator man-hours and the bandwidth necessary for ground-space communications. Fault isolation and recovery tasks are still performed by operators, however, and therefore it is necessary to develop methods to alert the mission control center of changes in spacecraft state requiring changes in the operations plan. The low-power, low-bandwidth beacon signal broadcast by the satellite announces the operational response required by the spacecraft at any given time. With very low-cost receiving stations, this signal can be relayed to mission control for proper, timely response.

For this project, SSDL's SAPPHIRE spacecraft will be modified to perform automated anomaly detection to assess its health state. This very low-bandwidth signal (two bits) will be broadcast on an intermittent basis. Very low-cost (around $1000) receiving stations, under development at SSDL, will receive the signal, identify the spacecraft health state, and relay this information to SSDL's ASSET operations system. This system will automatically log the incoming message and take appropriate action, up to and including rescheduling the network and paging operators to prepare to recover a failed spacecraft.

Once an end-to-end ground "proof of concept" test of the experiment is performed in December 1997, this experiment will await the launch of SAPPHIRE sometime in 1998. Once on-orbit, this health monitoring concept can be experimentally tested by performing non-beacon and beacon operations. The operator man-hours and communications link bandwidth for each method will be compared; it is expected that beacon-based monitoring will result in significant reductions in bandwidth and operator effort, with no loss of spacecraft performance.

1.2 The Space Systems Development Laboratory

Established in 1994, Stanford's Space Systems Development Laboratory was chartered to perform world-class research in all areas of spacecraft design, fabrication, and operations. The laboratory achieves these goals through classroom education, project experience, and student research. As part of the Masters degree curriculum, students can get involved in one of the lab's student-directed satellite projects. Two spacecraft, SAPPHIRE and OPAL, are currently in development. SAPPHIRE is further described in Section 2.3.

One of the primary areas of research in SSDL is in the area of spacecraft operations and automation. The beacon-based health monitoring experiment described in this paper is one of their main projects, and is being used to integrate the Automated Space Systems Experimental Testbed (ASSET) system, further described in Section 2.2.

For the beacon experiment, the following students and faculty are involved:

Professor Robert Twiggs (SSDL Director): Project Oversight
Christopher Kitts (PhD Candidate, Mechanical Engineering): Project Oversight, ASSET System Architecture, SAPPHIRE Operations Lead
Michael Swartwout (PhD Candidate, Aeronautics & Astronautics): Project Oversight, ASSET Software Programming, SAPPHIRE Project Manager
Brian Engberg (PhD Candidate, Aeronautics & Astronautics): ASSET Scheduling, SSDL Ground Station Manager
Carlos Niederstrasser (Engineers Candidate, Aeronautics & Astronautics): Beacon Receiving Station
Raj Batra (PhD Candidate, Aeronautics & Astronautics): SAPPHIRE Software Lead

1.3 Academic Contributions

The work performed on this project has resulted in many papers and conference publications. Most notably, Kitts and Swartwout presented their "Beacon Monitoring System for Automated Fault Management Operations" paper at the 1996 AIAA/USU Conference on Small Satellites in Logan, Utah; the follow-up report, "Automated Health Operations for the SAPPHIRE Spacecraft" will be presented at the 1997 International Telemetering Conference in Las Vegas, Nevada. The special software needed for this mission was described in Batra's "Designing a Flexible Operating System for SQUIRT Spacecraft" at the 1997 AIAA/USU Conference on Small Satellites. Two more papers, Kitts' "An Advanced Client Interface for Requesting Space Mission Products" and Swartwout's "Approaches to Engineering Data Summary for Space Missions" will be presented at the 1998 IEEE Aerospace Conference in Colorado. All of these papers are listed in Section 5.

The results of the proof of concept experiment will be presented at the 1998 SpaceOps conference in Tokyo. Moreover, the beacon-based health monitoring concept and experiment directly contributes to the PhD dissertations of Kitts (June 1998) and Swartwout (October 1998), and the Engineer's Degree thesis of Niederstrasser.

2.0 Project Outline

System health management is a specific mission operations task that has been enhanced through the use of automation technologies. The space industry routinely uses ground based expert systems to analyze spacecraft telemetry and detect the existence of faults. While this model has proven to be beneficial in reducing the workload of human controllers during nominal operations, it still requires full use of scarce ground equipment and bandwidth resources in order to deliver spacecraft telemetry to the control center.

To address this drawback, many developers in the spacecraft community advocate the migration of detection capability from the ground to on board the spacecraft. This new model requires the on-board reasoning system to perform realtime health assessment and to use a "beacon" to report the vehicle's status to the mission control center. Composed of, at most, a few bits of information, this beacon signal will summarize the spacecraft's status. When healthy, a "Normal" or "I'm OK" signal will reduce the need for routine health assessment contacts thereby conserving resources. When a fault exists, an "Emergency" or "Help Me" signal will trigger notification of controllers and can be used to initiate a variety of contingency operation functions.

While promising significant reductions in the cost of staffed operations and the time to detect and respond to a fault, the health monitoring beacon model of fault detection poses a number of additional design challenges. To prove the value of the beacon monitoring concept, SSDL is preparing to conduct a real world evaluation through the use of microspacecraft and a global, automated space operations network. This approach consists of automated fault detection on board a spacecraft, a state of health beacon signal broadcast by the spacecraft, a ground based monitoring network, and a mission control center capable of efficiently integrating this health assessment strategy into its operating architecture.

The experiment will be performed using the SAPPHIRE spacecraft, under development by SSDL, using the automated beacon receiving station and the mission control system at Stanford University. Each aspect of the project is introduced in this section, with implementation details provided in Section 3. Section 4 describes the tests that will be performed to demonstrate the concept and verify the performance

2.1 Beacon-Based Health Management Overview

A brief overview of the health monitoring beacon signal flow is presented here and shown in Figure 1. SAPPHIRE will monitor its own telemetry sensors, comparing measured values with commandable entries in a state-dependent limit table. Depending on the seriousness of the limit violation, the spacecraft health is assessed to be one of four values. The health beacon is transmitted by SAPPHIRE's main transmitter. Simple, receive-only stations will listen for SAPPHIRE beacon transmissions and notify mission control of the results by electronic mail. These stations will be in locations around the world, giving SAPPHIRE (and other spacecraft in the network) near-global coverage for health monitoring.

In this manner, all spacecraft sensor data is compacted into a few bits that tell an operator whether or not SAPPHIRE can continue to perform its mission. And while such information once had to be collected over time for eventual download and processing at mission control, spacecraft health is now continuously monitored and available anytime the spacecraft is within range of a low-cost receiving station. Once mission control receives a beacon monitoring update from a remote station, it logs this information and then takes appropriate action. Depending on the health assessment, there are varied responses, from storing the update in the system database to paging the operator on call, and rescheduling the network to contact the satellite.

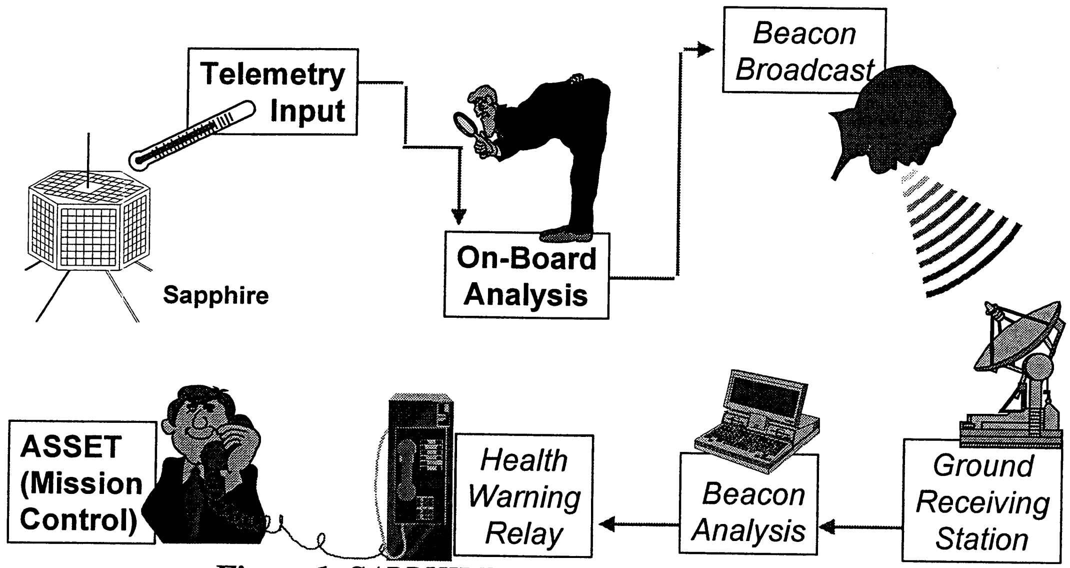

Figure 1: *SAPPHIRE Health Beacon Signal Flow*

2.2 The ASSET System

The health monitoring beacon experiment is the first implementation of the Automated Space Systems Experimental Testbed (ASSET) system under development at Stanford University. The primary goal of this system is to enable low-cost and highly accessible mission operations for SQUIRT microsatellites as well as other university and amateur spacecraft. The second goal of this system is to serve as a comprehensive, low inertia, flexible, real-world validation testbed for new automated operations technologies. Figure 2 shows a high level view of the ASSET mission architecture. The basic components include the user interface, a control center, ground stations, communications links, and the target spacecraft. During the current developmental phase, a highly centralized operations strategy is being pursued with nearly all mission management decision making executed in the control center. These tasks include experimental specification, resource allocation throughout the ground and space segment, health management, contact planning, data formatting and distribution, and executive control.

Mission operations elements, such as experiment requests, planning, scheduling and health management are automatically handled in ASSET through a blackboard system. A blackboard system is a software architecture wherein all the problem-solving elements, or knowledge experts, collaborate to solve the global task by working on a collective database, or blackboard. ASSET's blackboard system is a modified version of BBK, whose source code is freely distributed by its developer, Dr. Barbara Hayes-Roth of Stanford's Knowledge Systems Laboratory.

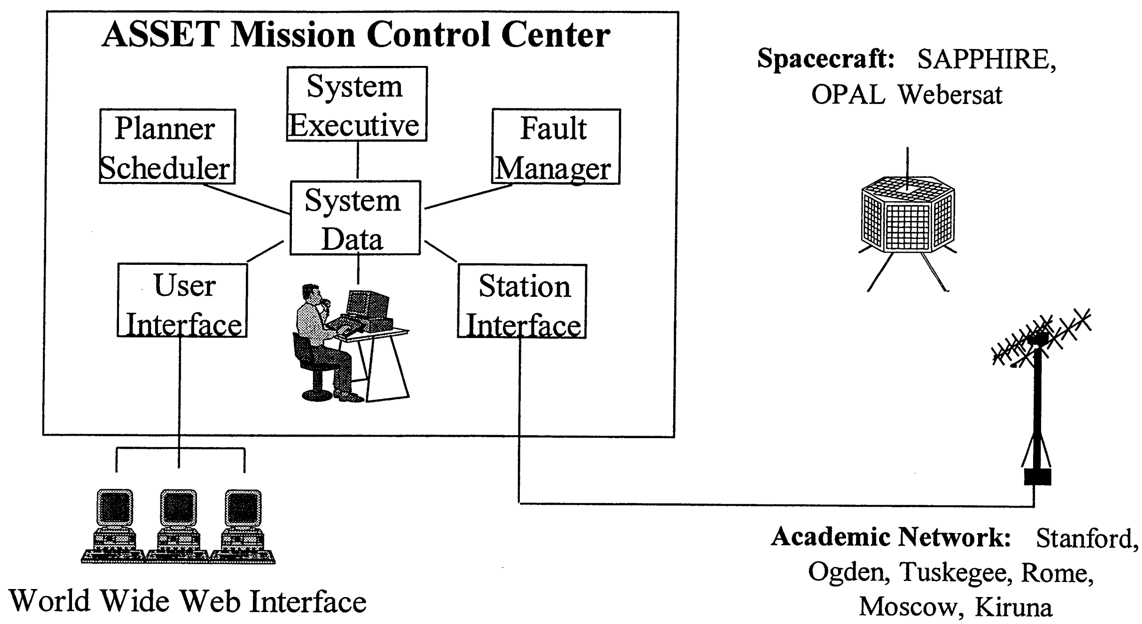

***Figure 2:** The ASSET Space System Architecture*

2.3 The SAPPHIRE Spacecraft

SAPPHIRE is a student-designed, student-built spacecraft that is fully functional and is nearing the end of its environmental acceptance tests. The spacecraft will be ready to launch in the first quarter of 1998, some four years after a nearly all-volunteer group of spacecraft design novices took up the task of building a satellite given less than $50,000 for all parts and testing.

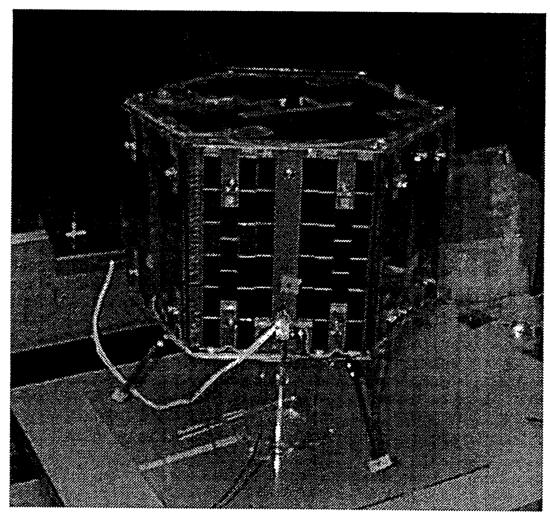

***Figure 3:** The SAPPHIRE Spacecraft*

SAPPHIRE is an acronym for **S**tanford **A**udio**P**honic **PH**otographic **I**nfra**R**ed **E**xperiment. Those letters describe the three instrument-based missions of this project. The infrared detectors are a next-generation micromachined horizon detector, operating at room temperature at about one Watt. A voice synthesizer broadcasts an FM "computerized" voice. A digital camera takes pictures of the Earth. In addition, several other missions advance basic research in spacecraft automation and operations, including the beacon-based health management described in this report. But SAPPHIRE's primary mission is to train students in all aspects of spacecraft design, fabrication, testing and operations.

Shown in Figure 3, SAPPHIRE is a hexagonal cylinder made from aluminum honeycomb, 17" from tip to tip and 13" tall (including launch interface). It has a total launched mass of 18kg (40 pounds) and is seeking secondary launch opportunities. The spacecraft is passively stabilized to follow the Earth's magnetic field, with a slight spin about its top axis. It communicates on the 70cm and 2m Amateur Radio bands. The operator software is student-written for the MC68332 microcontroller, acting as a UNIX-like bulletin board system. The design emphasizes the use of commercial, "off-the-shelf" parts.

When the spacecraft is unavailable for development – due to thermal vacuum testing or other circumstances – testing will be performed on "Al Wood", SAPPHIRE's fully functional prototype. Al Wood is equivalent to SAPPHIRE in all aspects save environmental packaging and will be available for use even after SAPPHIRE has been launched.

3.0 Project Status

The beacon-based health monitoring experiment has been divided into several portions. The five elements are: Health Assessment, Beacon Broadcast, Beacon Receiving Station, Automatic Notification, and System Resource Allocation. Table 1 gives a brief description of each element and its implementation status. "Delivery" indicates when a version of that element will be ready for the proof of concept test. All elements are further described, below. Note that the section headings include the names of the students responsible for providing that element.

Element	Location	Description	Status	Delivery
Health Assessment	SAPPHIRE	Analog Sensors State-Based Limits Automated Health Assessment	Simulated Software Concept Approved Code in Development	October 1997
Beacon Broadcast	SAPPHIRE	Low-Power Transmission Simple Signal	Prototype in Operation Trade Study for Flight	November 1997
Receiving Station	Worldwide	Unmanned Receive-Only Forwards Updates to ASSET	Preliminary Hardware Trade Study for Flight	December 1997
Automatic Notification	ASSET	Logs All Updates Analyzes Message Notifies Scheduler & Operator of Alarms	"Proof of Concept" Test Version Delivered	June 1997
System Resource Allocation	ASSET	Schedules Ground Contacts Offloads Experiments to Other Spacecraft Briefs Operators	Blackboard Implemented Scheduler Prototype Implemented In Integration & Test	December 1997

Table 1: *Beacon-based Health Management Elements*

3.1 Health Assessment (Kitts/Swartwout/Batra)

SAPPHIRE has two operating modes, Normal and Safe. Normal Mode allows full use of all payloads and functions aboard the spacecraft, within the usual restrictions governed by the user's login status. Safe Mode is intended to protect the spacecraft from mission-threatening conditions such as low battery voltage; entering Safe Mode causes all payloads to be turned off, all users to be logged off, and access restricted to a single "root user" - the SSDL mission operations team. The spacecraft remains in Safe Mode until the root user resets it to Normal Mode.

Given these two operating modes, four spacecraft health states are defined. These states map directly to the classes of responses an operator would take, and they are described in Table 2. If all components on the spacecraft are determined to be functioning normally – all sensors are within their defined limits – the health assessment is determined to be Normal. Abnormal health means one or more sensors are in their "yellow limits", which is a condition the operators should be aware of but which does not immediately threaten the health of the spacecraft. (Or, as is often the case for SAPPHIRE, it indicates an out-of-limits state that is not easily controllable by ground command.) Critical health indicates a vital components is dangerously out-of-limits, such as low battery voltage; the spacecraft CPU will put itself into Safe Mode as described above. When power cycle or radiation hit causes the CPU to reses, it boots up in the Emergency health state; this unexpected reset calls for different operational procedures than for Safe Mode.

Mode	Health	Vehicle Mode	Vehicle Status
1	Normal	Normal	Healthy
2	Abnormal	Normal	Out of Limit Telemetry
3	Critical	Safe	CPU Controlled Safe Mode
4	Emergency	Safe	CPU Reset Induced Safe Mode

Table 2: *SAPPHIRE Beacon States and Vehicle Modes*

SAPPHIRE contains 32 analog sensors, measuring such items as battery voltage, solar panel currents, transmitter temperature and payload sensor outputs. These measurands, and their high and low limits, are detailed in the Appendix. In addition, the operating system allows for 32 "customizable sensors." These are essentially counters to track user-defined variables.

Health monitoring is performed once every minute using a table system that is native to the spacecraft operating system. Table rows can be added or deleted and new tables can be created according to uploaded commands. A table row contains the identifier of the sensor to be examined, the upper and lower limits of the sensor, the persistence counter for this sensor, and the actions to take should the sensor be deemed out-of-limits. A sample table is presented in Table 3. First the CPU temperature and battery voltages are tested against the "Abnormal" limits; for each component that is assessed to be out of limits, a user-defined counter is incremented. Then, the battery voltage is checked again against its "Critical" limits and the appropriate counter may be incremented. Finally, the "Critical" counter is checked; if even one component has been found to be in a critical state, a string of actions are implemented to put the spacecraft in Safe Mode.

Sensor	Low	High	Persistence	Action(s)
CPU	0°	30°	5	Increment "Abnormal" Counter
Battery	12.0 V	16.0 V	3	Increment "Abnormal" Counter
Battery	11.5 V	-	3	Increment "Critical" Counter
"Critical" Counter	-	1	1	Health Assessment = "Critical"; Spacecraft Mode = "Safe"; Turn Off Payloads; Log Off Users; Allow Only Root User

Table 3: *Sample Health Assessment Table*

The concept of persistence has been included to account for sensor noise and to avoid rapid changes in state due to a sensor cycling near the limit boundaries. For a measurand to be considered "out of limits", it must persist in exceeding the designated bounds. A counter keeps track of the number of samples the measurand is too high or low, incrementing or decrementing as appropriate. When the counter matches the persistence value, the measurand is considered to be out of limits. The same holds true for the reverse; a measurand must persist inside the limits before it is considered to be normal again.

The limit values are commandable so that analysis can evolve with normal operating conditions. For example, solar panel current limits will be modified over time so that solar cell degradation will not be detected as a fault. In addition, the SAPPHIRE limit checking system can operate at an aggregate level in order to provide more focused analysis. For instance, the current from a single solar panel will typically vary between zero and some maximum normal level of output. An additional and much stronger check can be made, however, by ensuring that not all solar cells are near their maximum level, since SAPPHIRE's geometry prevents the sun from illuminating all panels at once. Finally, SAPPHIRE's limit checking is context sensitive so that different expected ranges are applied to realtime telemetry based upon the estimated state of the vehicle. An example of this is that during an eclipse the battery should be discharging. This approach is implemented by creating different tables for eclipse conditions and sunlight conditions; an assessment is made first to determine whether the spacecraft is in sunlight or eclipse and then the appropriate table is used.

A strawman anomaly detection simulation was developed and tested in the summer of 1996. The concept for the flight software implementation has been developed and was approved in August 1997. Preliminary work has been completed on the flight software commands. This software is currently being written and added to the flight code. It is expected that a functional version of the health monitoring code will be tested in October 1997.

3.2 Beacon Broadcast (Swartwout/Batra/Niederstrasser)

The spacecraft health state is then broadcast as a low-power, low-data-rate beacon. For Sapphire, the four possible health states can be expressed in a two bit signal. The beacon transmits this signal on a frequent (every one to two minutes) basis. The signal will be broadcast on SAPPHIRE's transmitter frequency, 437.100 MHz (70cm band).

Exact specifications for the beacon broadcast are still being determined; SAPPHIRE can implement the beacon digitally through a feature of its on-board radio modem, or pseudo-digitally by pulse modulation of the transmitter's carrier wave using the voice synthesizer payload. The pseudo-digital signal can be interpreted by a digital signal processor, converting the pulse modulation to ones and zeroes. Final decision on the mode of implementation requires a trade study involving spacecraft power consumption and duty cycle, complexity of generating the pulse modulation, and receiver link budget. This work will be completed in November 1997.

For prototype development, a simple ASCII beacon was implemented in June 1996 using the capabilities of SAPPHIRE's radio modem, and is still available for use.

3.3 Beacon Receiving Station (Niederstrasser)

The next stage of the monitoring system is the reception of the beacon signal. Except for the times when SAPPHIRE is in contact with ground operators, the beacon is broadcasting. Simple, receive-only, HAM radio frequency stations are being designed to acquire the two-bit beacon signal. These stations will accommodate multiple vehicles and will forward received signals to mission control centers through Internet or modem connections. Primary development of the receiving station for the SAPPHIRE/ASSET experiment is being conducted at Stanford University; educational initiatives have been established with Tuskegee University, Montana State University, and the Space Engineering School in Kiruna, Sweden to create a global network.

The receiving station is in the developmental stage, but basic requirements have been identified. Each station is intended to be low-cost ($1000) and operationally autonomous; the station does not track the spacecraft, nor does it require an operator to activate the receiver, interpret the incoming signal, or relay the information to the ASSET mission control. A functional prototype will be available in December 1997.

3.4 Automatic Notification (Swartwout)

When the mission control center receives an update from the remote receiving station, a series of actions take place. First, this message is automatically logged in the system database. Next, the content of this message is analyzed for pertinent data. If the health state indicated for that particular spacecraft warrants further action, the scheduling system of ASSET is notified, and an operator may also be paged.

These tasks have been implemented by a set of C functions running on a UNIX platform. As shown in Figure 4, A single process checks for incoming mail, parses the beacon messages, stores the information in the system database, and looks for alarms. If an alarm is detected, it sends a message (via a UNIX socket) directly into the scheduling system of ASSET (see below). Alarms of a serious nature (requiring prompt operator action) cause this process to send electronic mail to the operator. Several commercial Internet service providers can link a pager to an electronic mail account, allowing for near-instantaneous operator notification.

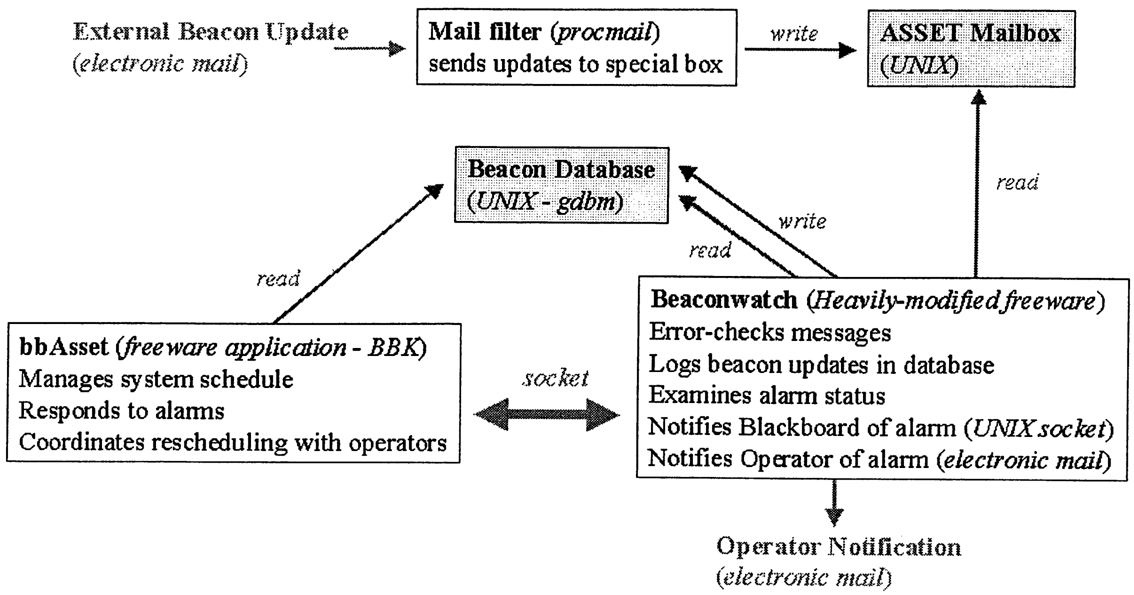

Figure 4: *Automatic Notification Schematic*

This element of the health monitoring system was demonstrated in June 1997 during a visit to JPL by members of the SSDL team, and is ready for the end-to-end test.

3.5 System Resource Allocation (Kitts/Engberg/Swartwout)

The final element of the health monitoring system is prepare the operations network to service this spacecraft. A Normal health state requires no changes, of course, since the operations plan assumes normal state. For SAPPHIRE, the Abnormal state involves minimal changes in operations, since operators have little or no controllability of the components involved in determining the Abnormal conditions. Beyond flagging a note for operators, no response is needed.

If SAPPHIRE's health state is either Critical or Emergency, a number of more involved functions are performed. First, SAPPHIRE experiments are postponed or canceled. Second, ground station support for SAPPHIRE is scheduled. Third, the schedules of other ASSET spacecraft are reworked to account for changes in ground station availability and experimental loading.

The ASSET blackboard system is in development, with a basic scheduling system currently undergoing testing. This scheduler, when implemented, will allow for a functional demonstration of the responses ASSET takes to a health emergency. This element will be ready for functional demonstrations in December 1997.

Although not formally part of the initial SAPPHIRE/ASSET beacon system, automated documentation retrieval and advanced fault isolation, diagnosis, and recovery techniques are being developed in order to aid the operator once full fledged contingency analysis begins. This capability is essential to the success of the beacon concept since operators will not be intimately familiar with spacecraft behavior once automated fault detection capability is established and trusted. In later versions of the beacon system, on-board health summarization will be included; this will enable the advanced documentation and health management functions to be integrated directly into the overall beacon monitoring system.

An open issue in the design of ASSET's response is how to deal with on-board mission data when the CPU initiates a vehicle Safe Mode. All of SAPPHIRE's data is stored in active memory; should the CPU reset, all data is lost. ASSET must terminate active experiments or reschedule them to collect data that was lost. But in a CPU initiated Safe Mode, the data is likely to still be on board and intact. Because of fault analysis and recovery requirements, there may be some time before this data can be returned to the control center, or it may be lost during the recovery process. To ignore data that is available, however, is an inefficient use of limited spacecraft and ground resources. The trade, then, is to determine the conditions under which the data "trapped" on Sapphire should be salvaged or given up for lost. This issue is being resolved through experimentation and assessment of the beacon system.

4.0 Future Work

The immediate goal of this project is to prepare all the elements for an end-to-end test; this will serve as a proof of concept. The next step is to demonstrate that this approach is an improvement over normal, operator- and contact-intensive operations by reducing the man-hours needed for operations and conserving communications bandwidth. This validation can be initially performed with SAPPHIRE operating in SSDL's clean room. Full validation will be performed once SAPPHIRE is in orbit. Exact details of these tests can be found in the Beacon-Based Health Monitoring Requirements Document and Design Document, referenced below.

4.1 Timeline to End-to-End Test

As explained in Section 3, the next major step in the project is to implement and test the added features of the flight software. This will take place in October 1997. Simultaneously, a first-cut version of the scheduling software is being developed; this will allow a functional demonstration of ASSET's ability to automatically reschedule in the event of a health emergency.

Once these two elements are functional, an initial demonstration of the system is possible. A text beacon is already implemented on the spacecraft; the messages can be read when the ground station is listening on that frequency. Thus, the spacecraft can automatically generate beacon messages; a human operator is needed to decipher and manually send the electronic mail update to the ASSET control center. The logging, notification, and replanning tasks will be automatically performed.

The final element is the beacon receiving station. Since Stanford took the development lead of this element only recently, it is still in the tradeoff stage. Expectations are high for rapid development and a working prototype by early December. Once the receiving station is functional, it will be inserted into the rest of the system and a complete end-to-end demonstration will take place in December 1997.

4.2 Ground Tests of Validation Experiment

Once SAPPHIRE is fully ready for flight, it will be locked away inside SSDL's clean room for no less than thirty days of operational checkout. Since the health monitoring beacon experiment is one of SAPPHIRE's missions, there will be time to perform demonstrations and tests of the concept in flight-equivalent conditions. SAPPHIRE will remain operational from inside the clean room while it waits for a secondary launch, so there could be significant time available for ground tests of the validation experiment.

4.3 Flight Validation

Once the spacecraft passes initial checkout and data for the THD primary payload has been sufficiently collected, this beacon-based health monitoring concept will be tested. First, data will be taken for a "routine" week of operations, keeping track of the number and duration of contacts required to perform health management tasks. The time spent by operators in performing these tasks will also be recorded. Then the health monitoring beacon system will be activated and the same information will be collected.

Provided that the spacecraft has the same general performance during these two weeks, such as similar duty cycles for instruments and similar numbers and types of anomalies, a comparison can be made regarding the cost of performing beacon-based health management. Again, it is expected that the cost of operations, as measured by operator man-hours and communications bandwidth, will decrease. Given that identical methods for anomaly detection will be used in the ground-based and space-based cases, there is no projected improvement in the quality of prediction, though tests can also be run on this subject; there may be some improvement due to the fact that the on-board anomaly detection occurs much more frequently than is possible on the ground. For the same reason, the response time to an anomaly may also decrease, but there are complex effects related to paging an operator from outside the mission control center, and also the time required for an operator to get "up to speed" on the state of the spacecraft.

4.4 Additional Studies

Of course, the issue raised at the end of Section 4.3 warrants further investigation. Operators used to be very familiar with the spacecraft they monitored – or they had an extensive historical telemetry archive to allow them to get familiar with the performance of every component. However, in beacon-based health management the *spacecraft* is responsible for the routine sensor analysis, which means that the telemetry data is rarely, if ever, sent to the ground. Reduced bandwidth is, of course, one of the primary goals of beacon-based monitoring.

Without this historical archive, it is necessary to provide other means of providing operators with the information necessary to perform health management duties. One possible solution has been termed the engineering data summary, which is already under investigation at JPL and other institutions. The idea is to perform additional on-board analysis to provide a summary of the vital information about spacecraft components that will aid operators in performing complex tasks like anomaly isolation and fault recovery. Research continues at SSDL into developing solutions to this problem. As time and on-board memory allows, SAPPHIRE will be used as a testbed for data summary approaches.

The ASSET system was conceived to allow rapid prototyping of different concepts for all aspects of spacecraft operations. It is a research tool that will allow beacon, summary, and other approaches to be tested in a real-world environment.

5.0 References

This report draws on the work currently being performed at Stanford University by the Space Systems Development Laboratory. Listed below are the pertinent documents related to SSDL's beacon-based health monitoring experiment.

Official Documentation:

ASSET Health Management Subsystem Requirements Document, available online in PDF format at: http://aa.stanford.edu/~ssdl/projects/asset/hlthspec.pdf

The SAPPHIRE Microsatellite Project, August 1997, available online in PDF format at: http://aa.stanford.edu/~ssdl/projects/squirt1/pdf/design97.PDF

ASSET Health Management Subsystem Design Document, available through SSDL.

Published Papers:

Swartwout, Michael A., and Christopher A. Kitts, "Automated Health Operations for the SAPPHIRE Spacecraft", June 11, 1997, Pending publication in ITC/USA '97: Proceedings of 33rd Annual International Telemetering Conference, October 30- November 1, 1997, Las Vegas, NV.

Kitts, Christopher A., and Michael A. Swartwout, "Experimental Initiatives in Space Systems Operations", July 10, 1997, Pending publication in Proceedings of the Annual SatelliteCommand, Control and Network Management Conference, September 3-5, 1997, Reston, VA.

Batra, Raj, "Designing a Flexible Operating System for SQUIRT Spacecraft", June 1, 1997, Proceedings of the Eleventh Annual AIAA/USU Small Satellite Conference, September 15-19, 1997.

Kitts, Christopher A., and Clemens Tillier, "A World Wide Web Interface for Automated Spacecraft Operation", July 10, 1996, ITC/USA '96: Proceedings of 32nd Annual International Telemetering Conference, October 28-31, 1996.

Swartwout, Michael A., and Christopher A. Kitts, "A Beacon Monitoring System for Automated Fault Management Operations", June 13, 1996, Proceedings of the Tenth Annual AIAA/USU Small Satellite Conference, September 16-19, 1996.

Kitts, Christopher A., "A Global Spacecraft Control Network for Spacecraft Autonomy Research", June 1, 1996, SpaceOps '96: Proceedings of the Fourth International Symposium on Space Mission Operations and Ground Data Systems, September 16-20, 1996.

Upcoming Papers:

Swartwout, Michael A., "Approaches to Engineering Data Summary for Space Missions", December 10, 1997, To be published in the Proceedings of the 1998 IEEE Aerospace Conference, March 21-28, 1998, Snowmass, CO.

Kitts, Christopher A., "An Advanced Client Interface for Requesting Automated Space Mission Products: Balancing High-Level Specification with Low-Level Control", December 10, 1997, To be published in the Proceedings of the 1998 IEEE Aerospace Conference, March 21-28, 1998, Snowmass, CO.

Appendix: SAPPHIRE Telemetry Information

Each of SAPPHIRE's 32 sensors are listed, along with its expected high and low values for both Critical and Abnormal states, plus some of the 'custom' channels. Note that many sensors do not have values for Critical; this is because those components do not pose a threat to the health of the entire spacecraft and/or there is no means to control their output through ground commands.

Channel Number	Telemetry	Crit Low	Abnrml Low	Nom	Abnrml High	Crit High	Notes
0	SP 2 Current	-	-	244	1000	-	Milliamps
1	SP 1 Current	-	-	244	1000	-	Milliamps
2	SP 4 Current	-	-	244	1000	-	Milliamps
3	SP 3 Current	-	-	244	1000	-	Milliamps
4	Battery 2 Temp	-	-20	0	30	50	Celsius
5	Battery Voltage	10.5	11.0	12.2	14.5	16.0	Volts
6	SP 6 Current	-	-	244	1000	-	Milliamps
7	SP 5 Current	-	-	244	1000	-	Milliamps
8	+5 Volts	-	4.75	5.0	5.25	-	Volts
9	+12 Volts	-	11.4	12.0	12.6	-	Volts
10	SP 8 Current	-	200	488	2000	-	Milliamps
11	SP 7 Current	-	200	488	2000	-	Milliamps
12	Battery Charge	-	-	200	*5000*	-	bits
13	Battery Current	-	-	212	1000	-	Milliamps
14	Earth Sensor A	-	-	0.3	*4.0*	-	Volts
15	Earth Sensor B	-	-	0.3	*4.0*	-	Volts
16	THD 1 Signal 1	-	-	-	-	-	Science signal
17	THD 1 Signal 2	-	-	-	-	-	Science signal
18	THD 1 High Voltage	-	200	250	300	-	Volts (when off)
19	THD 1 Temperature	-	0	15	30	-	Celsius
20	THD 0 Signal 1	-	-	-	-	-	Science signal
21	THD 0 Signal 2	-	-	-	-	-	Science signal
22	THD 0 High Voltage	-	-	-	20	-	Volts (when on)
23	THD 0 Temperature	-	0	15	30	-	Celsius
24	Fotoman Temp	-	5	15	40	-	Celsius
25	Transmitter Temp	-	-10	20	50	-	Celsius
26	SP 8 Temperature	-	-10	20	80	-	Celsius
27	SP 1 Temperature	-	-10	20	80	-	Celsius
28	SP 7 Temperature	-	-10	20	80	-	Celsius
29	SP 4 Temperature	-	-10	20	80	-	Celsius
30	Battery 1 Temp	-	-20	0	30	50	Celsius
31	CPU Temperature	-	-10	0	40	-	Celsius
32	Health Indicator	-	-	1	2	3	Custom Channel
33	Sunlit Panel Counter	-	-	3	5	-	Custom Channel
34	Abnormal Counter	-	-	0	1	-	Custom Channel
35	Critical Counter	-	-	0	-	1	Custom Channel